Naval Research Laboratory
Stennis Space Center, MS 39529-5004

NRL/MR/7332--97-8068

A Three-Year Climatology of Waves and Winds in the Gulf of Mexico

WILLIAM J. TEAGUE
PAUL A. HWANG
GREGG A. JACOBS

Ocean Sciences Branch
Oceanography Division

E. F. THOMPSON

Coastal Engineering Research Center
Vicksburg, MS

DAVID W. WANG

Computer Science Corporation
Stennis Space Center, MS

November 14, 1997

REPORT DOCUMENTATION PAGE

Form Approved
OBM No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
November 14, 1997

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
A Three-Year Climatology of Waves and Winds in the Gulf of Mexico

5. FUNDING NUMBERS
Job Order No. 573704607
Program Element No. 0603832D
Project No. DMSO-97-0117
Task No.
Accession No.

6. AUTHOR(S)
William J. Teague, Paul A. Hwang, Gregg A. Jacobs, E. F. Thompson*, and David W. Wang†

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Oceanography Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/MR/7332--97-8068

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Oceanography Division
Stennis Space Center, MS 39529-5004

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
*Coastal Engineering Research Center, Vicksburg, MS 39180-6199
†Computer Science Corporation, Stennis Space Center, MS 39529

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Precise wave and wind climatologies from satellite data are now possible. Significant wave height, wave period, wave steepness, and wind speed over the Gulf of Mexico have been derived from the NASA altimeter on the TOPEX/POSEIDON satellite for 1992–1995. TOPEX/POSEIDON ground tracks in this region are approximately 300 km apart and have an along track resolution of about 7 km. Climatological maps of the Gulf of Mexico for these parameters have been generated for annual and seasonal time periods. Strong seasonality is clearly shown from these maps. Wave heights and wind speeds are found to increase from east to west across the Gulf. The fall and winter seasons are found to be most intense, with the largest significant wave heights and highest wind speeds observed during the fall season of 1995. Summer seasonal values were typically very low. The satellite data compare well with the National Data Buoy Center (NDBC) in situ buoy data and Army Corps of Engineers Wave Information Studies (WIS) Gulf of Mexico wave hindcast model statistics. Statistics of wave parameters derived from TOPEX/POSEIDON are improved over earlier satellite missions due to the improvements in altimeter accuracy and longer satellite lifetime.

14. SUBJECT TERMS
altimeter, waves, wind, buoys, Gulf of Mexico

15. NUMBER OF PAGES
21

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

A THREE-YEAR CLIMATOLOGY OF WAVES AND WINDS IN THE GULF OF MEXICO

1 INTRODUCTION

Spaceborne sensors such as satellite altimeters provide long-term and continuous coverage of wave and wind fields of the world oceans. It has been shown convincingly that spaceborne altimeter measurements of significant wave height, H (henceforth referred to as wave height), agree with in situ buoy measurements to within 0.15 m (*Gower 1996*) and measurements of wind speed to about 1.8 m/s (*Freilich and Challenor 1994*). Recent study of tilting effects on radar backscatter indicates that the altimeter wind speed (U) measurements are accurate to better than 1 m/s (*Hwang et al. 1997a*), and are within the accuracy of buoy measurements. The combination of wind speed and wave height further yields the information of wave period (T) (*Hwang et al. 1997b*). It is therefore quite feasible that we can obtain the three critical parameters of a wave field (H, T and U) from satellite altimeters and can provide a long-term monitoring of the wave climate of the world oceans.

Measurements of H, T, and U are important for assimilating into numerical models, for forecasting of the weather, and for ocean circulation studies. Moored surface buoys are used to provide such data which have high resolution in time but are very limited in spatial coverage. In addition, buoy measurements are subject to a harsh environment that can introduce errors and loss of data. Satellites provide a broader coverage and have high resolution along track but have a lower time resolution as defined by the satellite's orbit. However, satellites have the advantage of using just a single instrument, in lieu of dozens of buoys, and operate in a relatively stable environment. Since the satellite coverage is global and the expected lifetime is better than five years, long term climate conditions can be studied. Currently, there are more than four full years of TOPEX/POSEIDON data. These data are suitable for averaging and gridding in order to produce climatological maps of waves and winds. For an initial effort the Gulf of Mexico is used as a testbed for studying the regional wave and wind properties.

This paper presents climatological maps of wave height, wave period, wave steepness, and wind speed for the Gulf of Mexico. The maps are spot-checked with buoy measurements for validation and are compared to Army Corps of Engineers Wave Information Studies (WIS) wave hindcast model statistics. Seasonal and yearly averages are presented.

2 SATELLITE DATA

Satellite data used in this study are from TOPEX/POSEIDON. Henceforth, it will be referred to simply as TOPEX. TOPEX was launched August 10, 1992 as a joint effort by the United States National Aeronautics and Space Administration (NASA) and the French Space Agency, Centre National d'Etudes Spatiales (CNES), for studying global ocean circulation (*Fu et al. 1994*). TOPEX data utilized in this study (Figure 1) are obtained from the Geophysical Data Records (GDRs) processed at the Physical Oceanography Distributed Active Archive Center (PODAAC) at the Jet Propulsion Laboratory. TOPEX has a repeat period of 9.92 days and an equatorial cross-track separation of 315 km. Along track resolution in the Gulf of Mexico is about 7 km. TOPEX measures the range from the satellite to the sea surface from which sea-surface height is obtained, significant wave height (the average height of the highest third of the waves), and the normalized radar backscatter cross section (σ_0) derived from the K_u band from which wind speed is derived. The footprint over which the wave and wind measurements are made ranges from about 10 to 70 km^2, depending on the sea state (*Chelton et al. 1989*). The wave height data and σ_0 are not interpolated along track for this analysis.

Equations for wave height, wind speed, wave period, and wave steepness are given below. See *Hwang et al. (1997b)* for more details in the equation development. Wind speed at 10 m above the sea surface, approximated with a fifth order polynomial fit of the tabulated data in *Witter and Chelton (1991)*, is given by

$$U = \sum_{k=0}^{5} a_k \sigma_0^k, \tag{1}$$

where $a_0 = -2.2188 \times 10^2$, $a_1 = 1.0649 \times 10^2$, $a_2 = -1.7309 \times 10^1$, $a_3 = 1.2955$, $a_4 = -4.6079 \times 10^{-2}$, and $a_5 = 6.3270 \times 10^{-4}$. Since Table 1 of *Witter and Chelton (1991)* was established using the GEOSAT backscatter data, 0.7 db is subtracted from the TOPEX cross section when applying the above algorithm (*Callahan et al. 1994*). Empirically, the peak period of the wave field, T, is related to wind speed, U, and wave height, H (*Hasselmann et al. 1976*), and is given by

$$U/(gT) = 0.048(U^2/(gH))^{0.67}, \tag{2}$$

where g is the gravitational constant. Using the TOPEX derived U and H, the period calculated from (2) is found to be slightly less (by 6%) than the buoy measured peak period (*Hwang et al. 1997b*). The wave number, K, corresponding to T is calculated from the deep water dispersion relationship (*Kinsman 1965*), given by

$$K = (4\pi^2)/(gT^2). \tag{3}$$

Defining the wave steepness as the product of wave number and wave amplitude (one-half of the wave height), the wave steepness can also be obtained from TOPEX. Comparisons of TOPEX and buoy measurements in the Gulf of Mexico indicate that the wave height rms difference is 0.15 m and that the wind speed rms difference is 1.2 m/s. The wave periods

derived from TOPEX are within 10% of the peak period measured by buoys. For a detailed comparison of buoy measurements of H, T, and U with TOPEX measurements, see *Hwang et al. (1997b)*.

In forming the climatological maps, the TOPEX data are averaged over one-degree squares. TOPEX data from one or more tracks that fall within any part of a square are used in the average for that square. The TOPEX data have high spatial resolution of about 7 km along track but have temporal resolution of only about 10 days for any particular track. In Figure 1, TOPEX tracks and grid are shown for the Gulf of Mexico along with buoy locations. The one-degree grid squares where there are TOPEX data are shaded. Although this averaging technique is primitive, over 75% of the grid squares are supported by data. An inverse distance averaging technique is used to interpolate grid values where there are no data. The data are then further interpolated to a 0.2 degree grid for smoothing purposes.

In this study, significant wave heights and wind speeds for the Gulf of Mexico are discussed for the 1993–1995 period. The analysis periods include the entire 1993–1995 period, each year, and the four seasons for each year. Winter is defined as January through March, spring as April through June, summer as July through September, and fall as October through December. Maximum values for wave height, period, steepness, and wind speed corresponding to the three-year period, each year, and season are provided in Table 1. Maximum values were computed by averaging the top 10% of the larger data values for each parameter.

In Figure 2, mean wave height, wind speed, wave period, and wave steepness are shown for the 1993–1995 period. Wave heights and wind speeds are found to be highest in the western Gulf of Mexico (about 1.3 m and 7 m/s respectively). Corresponding wave periods (about 5.5 s) are also longest for that region. However, wave steepness does not show a similar overall pattern, although several smaller regions of higher steepness are found in the western Gulf of Mexico.

Mean wave height and wind speed are shown for each individual year in Figures 3–5, and mean wave period and wave steepness are shown in Figures 6–8. Average wave heights are found to be larger in 1995 than in 1993 and 1994. Interannual variability is definitely present. For each year, mean wave height increases from east to west and ranges in amplitude from about 0.5 m off the coast of Florida to about 1.5 meters off the coast of Texas. Similarly, mean wind speed ranges from about 4 m/s to nearly 8 m/s. Wave periods range from about 3 to 6 seconds and wave steepness ranges from about 0.08 to 0.095. Wave heights are largest, particularly in the western Gulf of Mexico, in 1995 and smallest in 1993. Low wave heights are found along the coasts at water depths less than 100 m except for the north-south oriented coasts of Texas and Mexico.

Striking seasonal differences are found for wave height and wind speed. Maps of wave height and wind speed for individual seasons (Figures 3–5) show lowest wind speed and wave height for the summer period. Highest wind speeds and wave heights are found in fall and winter. Spring appears to be a transition period. Interestingly, lowest wind speeds for the three-year period are found for summer, 1995 and highest wind speeds are found for fall, 1995. Correspondingly, largest overall wave heights and wind speeds are found in fall,

1995.

Wave period and wave steepness for individual seasons are presented in Figures 6–8. Waves are generally steeper during the fall and winter, and less steep during spring and summer. However, steepness in summer, 1993 is relatively large compared to steepness in summer, 1995.

3 BUOY DATA

National Data Buoy Center (NDBC, part of the National Oceanic and Atmospheric Administration) buoys located in the Gulf of Mexico (see Figure 1) at water depths which ranged from about 20 m to depths deeper than 3000 m provide data for comparison with the satellite data. The buoys provide measurements of significant wave height, wave period, wind speed, atmospheric pressure, and air and sea temperature. Buoy wave height and wind speed estimates are available once per hour and are given to 0.1 m and 0.1 m/s, respectively. These measurements are not quite the same as the altimeter measurements since they are point measurements in time and space and are subject to their inherent instrumental problems (*Monaldo,1988*). Buoy data nearest in time to the TOPEX time are used in the comparisons.

In general, good agreement has been found between buoy and TOPEX wave heights for various regions. *Gower (1996)* found excellent agreement off the west coast of Canada and *Ebuchi and Kawamura (1994)* had favorable comparisons around Japan. Similar success was obtained using GEOSAT wave height and wind speed observations by *Dobson et al. (1987)* for selected buoys in the North Atlantic, North Pacific, and the Gulf of Mexico. We also find good agreement between buoy and TOPEX data in the Gulf of Mexico. Satellite wave heights are compared with NDBC data from the buoy located near the crossover of TOPEX track 20 and 115 (Figure 9a). These two data types are found to be in excellent agreement, within about a 0.16 m rms difference and a correlation of about 0.98. Wind speeds (Figure 9b) are also found to be in excellent agreement, within 1.25 m/s rms and a correlation of about 0.85 using the algorithms of *Brown et al. (1981), Witter and Chelton (1991)*, and *Freilich and Challenor (1994)*. Characteristic wave period calculated from TOPEX data and bouy measured wave periods are shown in Figure 9c. Wave period comparisons also show good agreement but appear to have more scatter than the wave height and wind speed comparisons. More extensive comparisons using all of the Gulf of Mexico buoys is presented in (*Hwang et al. 1997b*).

The climatological means for significant wave heights and wind speed shown in Figures 3–5 are compared with three NDBC buoys located in the central Gulf of Mexico near 26°N shown in Figure 1. TOPEX climatological seasonal means for wave heights and wind speeds at grid points along 26°N near these buoy locations, and buoy monthly means with standard deviations (smoothed over 3 months) are presented in Figure 10. As also observed in Figure 2, wave height and wind speed are larger at the westernmost buoy along 25.9°N. In general, TOPEX wave heights compare very well with the buoy measurements, particularly at higher

wind speeds. Agreement is well within the buoy standard deviation of about 0.6 m for wave height. Wind speeds compared well for the higher wind speeds but not as well for the lower wind speeds, as anticipated due to the larger scattering of backscattering cross section measurements under low wind speeds *Hwang et al. (1997a)*. Standard deviation of buoy wind speeds averaged about 2.7 m/s.

Twenty years (1956–1975) of hindcast wave data were output at 3-hr intervals for selected locations in the Gulf of Mexico by the U.S. Army Corps of Engineers (*Hubertz and Brooks 1989*) using the Wave Information Study (WIS) wind-driven shallow-water wave model (*Corson et al. 1980; Resio 1982*). The model has a one hour time resolution and a 0.25 degree grid. These model data, which compares favorably with in situ buoys, are valuable for analyzing statistics over long time periods and in comparisons with satellite measurements for cross validations. The model data provide broad area coverage like TOPEX but also provide the time resolution that TOPEX lacks. Providing that the model and TOPEX produce similar statistics, which preliminary comparisons indicate, the data sets can be very complementary. For example, three years (1993–1995) of data from TOPEX track 21 are compared with the 20 years of data at WIS station 9, less than 5 km in distance from the ground track (Figure 11). TOPEX wave heights are higher in all height ranges by about 3 to 8%, except for wave heights between 1.0 and 1.5m, where the WIS measurements are about 16% higher. The model hindcasts extend over a considerably longer time period (1976-95) than that covered by satellite or buoy measurements.

4 DISCUSSION

This work demonstrates that broad area climatological maps can be produced using data from TOPEX. The resolution of these maps can be increased by using additional satellites such as the European remote sensing satellite ERS-1 (launched in July, 1991) and the GEOSAT Follow-on satellite (scheduled for launch in mid-year 1997). In addition, a long time series of global wind speed and wave height data are available from GEOSAT for 1985 to 1990. These satellite data are comparable in accuracy to the buoy data. Although time resolution is much poorer than the buoy data, horizontal coverage is far greater than ever possible with buoy data alone. The data are quite complementary and can be used in combined analyses.

Seasonal maps of wind speeds were made for the 1990–1993 time period using meteorological stations along the periphery of the Gulf of Mexico by *Gutierrez de Velasco and Winant (1996)*. They find, as we do, that the smallest wind speeds occur off the coast of west Florida, Alabama, and Mississippi and increase towards the west. They find highest wind speeds near the Yucatan peninsula, where we also find high wind speeds. However, we find high wind speeds throughout the western Gulf of Mexico, where *Gutierrez de Velasco and Winant* lacked data coverage. In addition, they find as we find that the wind speeds can be described in terms of two seasons: fall and winter, and spring and summer. These seasons are also appropriate for H, T, and KA from altimeter data.

Encouraging results were also obtained from the WIS model. Validation of such a model is difficult but is possible using satellite data such as the TOPEX data set. Combined analyses of satellite data and model output can produce a Gulf of Mexico climatology which spans decades and perhaps more importantly, real-time wave forecasts. More work is needed for the model validation.

The broad area climatology maps from satellite measurements are particularly valuable as they provide data where there are no buoy measurements and give the overall picture of the wind and wave climate. Annual and seasonal distributions are presented here but monthly and even smaller averaging periods are feasible when multiple satellite data are analyzed. Such climatological maps will be very valuable in planning operations such as: commercial drilling, spill dispersion prediction, underwater construction, amphibious landings, and mine sweeping.

5 CONCLUSIONS

Sufficient data now exists for the development of wave and wind climatologies from satellite data. Measurements of wave height, wave period, and wind speed from TOPEX are accurate in the Gulf of Mexico and a climatology spanning 1993–1996 is quite feasible. Additional satellites, some of which are already scheduled for launch, are needed to increase the temporal and spatial coverage. TOPEX wave and wind data are output every second which translates to about 7 km along track resolution. For near-shore realizations, 10 Hz wave and wind data, which are at about 700 m resolution, are needed. TOPEX currently outputs sea-surface heights at 10 Hz resolution but outputs wave heights at only 1 Hz resolution. However, 10 Hz wave heights are planned for the GEOSAT Follow-on mission. A combination of satellite and model data will ultimately produce the best wind and wave climatologies.

Acknowledgments

The TOPEX/POSEIDON data were obtained from the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory, California Institute of Technology. Buoy data were obtained from the Nationa Data Buoy Center, Stennis Space Center, MS. This work was supported by the Naval Research Laboratory's Ocean Executive Agent Office (Job Orders 73-7046-06), the Office of Naval Research (Contract N0001496WX30445), and the National Data Buoy Center (Contract XA2310501).

REFERENCES

Brown, G.S., H.R. Stanley, and N.A. Roy, 1981. "The wind speed measurement capability of spaceborne radar altimeters," *IEEE J. Oceanic Eng., OE-6*, 59–63.

Callahan, P.S., C.S. Morris, and S.V. Hsiao, 1994. "Comparison of TOPEX/POSEIDON σ_0 and significant wave height distributions to Geosat," *J. Geophys. Res.,* **99**, 25,015–25,024.

Chelton, D.B., E.J. Walsh, and J.L. Macarthur, 1989. "Pulse compression and sea level tracking in satellite altimeters," *J. Atmos. and Oceanic Technol.,* **6**, 407–438.

Corson, W.D., D.T. Resio, and C.L. Vincent, 1980. "Wave Information Study of U.S. Coastlines; Surface Pressure Field Reconstruction for Wave Hindcasting Purposes, Report 1," *TR HL-80-11*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Dobson, E., F. Monaldo, J. Goldhirsh, and J. Wilkerson, 1987. "Validation of Geosat altimeter-derived wind speeds and significant wave heights using buoy data," *J. Geophys. Res.,* **92**, 10,719–10,731.

Ebuchi, N., and H. Kawamura, 1994. "Validation of wind speeds and significant wave heights observed by the TOPEX altimeter around Japan," *J. Oceanogr.,* **50**, 479–487.

Freilich, M.H., and P.G. Challenor, 1994. "A new approach for determining fully empirical altimeter wind speed model functions," *J. Geophys. Res., 99*, 25051–25062.

Fu, L.-L., E. J. Christensen, C. A. Yamarone Jr., M. Lefebvre, Y. Menard, M. Dorrer, and P. Escudier, 1994. "TOPEX/POSEIDON mission overview," *J. Geophys. Res.,* **99**, 24369–24381.

Gower, J.F.R., 1996. "Intercalibration of wave and wind data from TOPEX/POSEIDON and moored buoys off the west coast of Canada," *J. Geophys. Res.,* **101**, 3817–3829.

Gutierrez de Velasco, G. and C.D. Winant, 1996. "Seasonal patterns of wind stress and wind stress curl over the Gulf of Mexico," *J. Geophys. Res.,* **101**, 18,127–18,140.

Hasselmann, K., D.B. Ross, P. Miller, and W. Sell, 1976. "A parametric wave prediction model," *J. Phys. Oceanogr.,* **6**, 200–228.

Hubertz, J.M. and R.M. Brooks, 1989. "Gulf of Mexico Hindcast Wave Information," *WIS Report 19*, Coastal Engineering Research Center, Vicksburg, MS, 39181-0631.

Hwang, P. A., D. W. Wang, W. J. Teague, and G. A. Jacobs, 1997a. "Effect of surface tilting on altimeter wind measurements," *NRL/MR/7332-97-8067*, 22 pp.

Hwang, P. A., W. J. Teague, G. A. Jacobs, and D.W.-C. Wang 1997b. "Measurement of wind and wave parameters from satellite altimeters," *Proceedings of the Fourth International Conference on Remote Sensing for Marine and Coastal Environments*, **1**, 441–450.

Kinsman, B., 1965. *"Wind Waves"*, Prentice-Hall, Inc., 676 pp.

Monaldo, F., 1988. "Expected differences between buoy and radar altimeter estimates of wind speed and significant wave height and their implications on buoy-altimeter comparisons," *J. Geophys. Res.*, **93**, 2285–2302.

Resio, D.T., 1982. "The Estimation of Wind-Wave Generation in a Discrete Spectral Model," *WIS Report 5*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Witter, D.L., and D.B. Chelton, 1991. "A Geosat altimeter wind speed algorithm and a method for altimeter wind speed algorithm development," *J. Geophys. Res., 96*, 8853–8860.

	Wave Height (m)	Wave Period (s)	Wave Steepness (x100)	Wind Speed (m/s)
1993-1995	1.39	5.60	9.35	6.95
93	1.37	5.52	9.45	7.22
94	1.42	5.68	9.32	6.94
95	1.50	5.79	9.48	7.20
Win93	1.72	6.12	9.69	8.08
Spr93	1.48	5.76	9.71	7.69
Sum93	1.19	5.09	9.84	7.25
Fal93	1.63	5.90	10.03	8.58
Win94	1.98	6.63	9.68	8.92
Spr94	1.41	5.83	9.60	7.06
Sum94	1.29	5.53	9.65	6.46
Fal94	1.56	5.87	9.69	7.65
Win95	1.64	6.09	9.82	7.94
Spr95	1.49	5.76	9.75	7.58
Sum95	1.23	5.40	9.32	5.88
Fal95	2.14	6.78	10.05	9.54

Table 1. Maximum wave height, wave period, wave steepness, and wind speed for annual and seasonal time periods. The maximum value is calculated by averaging the top 10% of the larger data values.

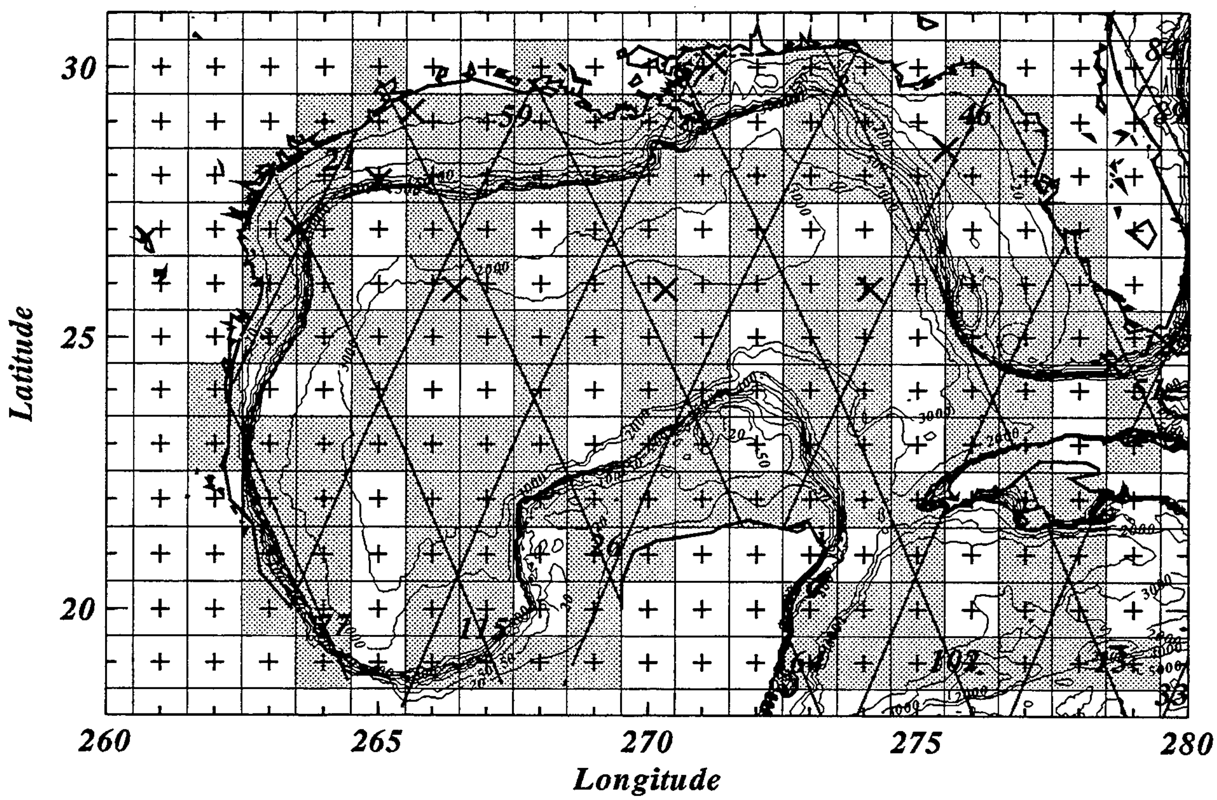

Figure 1. TOPEX tracks (heavy lines), NDBC buoy locations (x), bathymetry (thin lines), and grid (+) are shown for the Gulf of Mexico. Grid squares are shaded where there are TOPEX data.

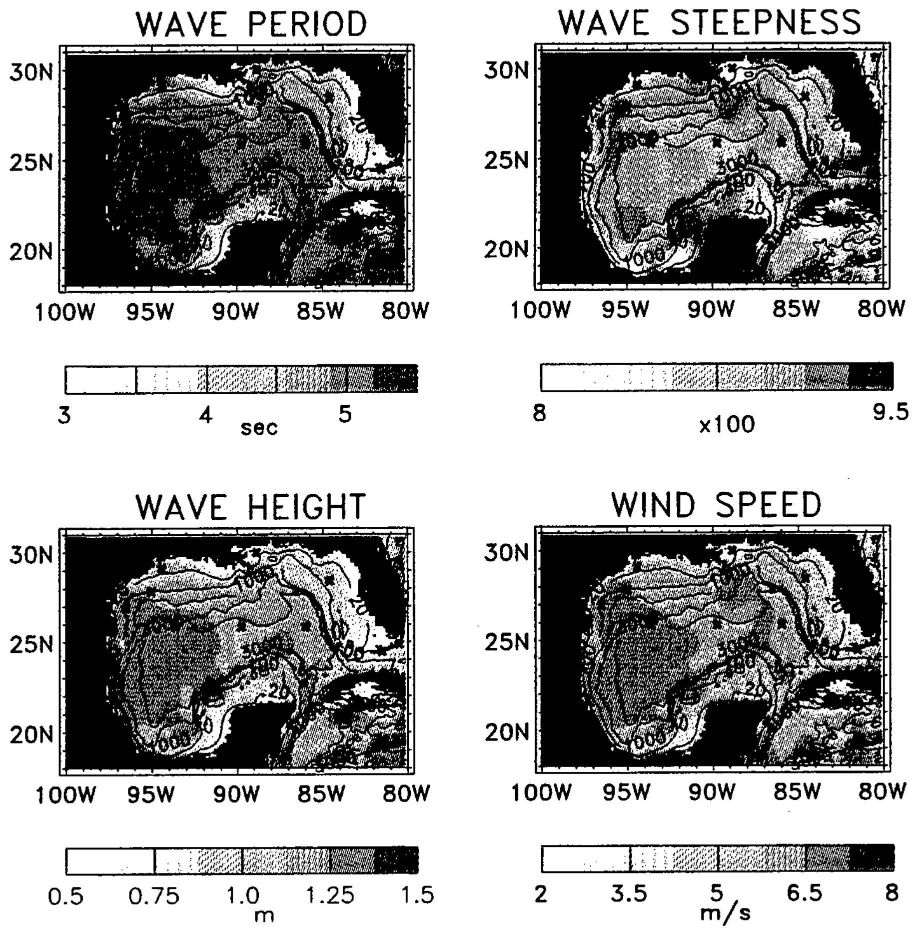

Figure 2. Mean significant wave height, wind speed, wave period, and wave steepness are shown for the 1993-1995 time period. Also shown are NDBC buoy locations (x) and bathymetry.

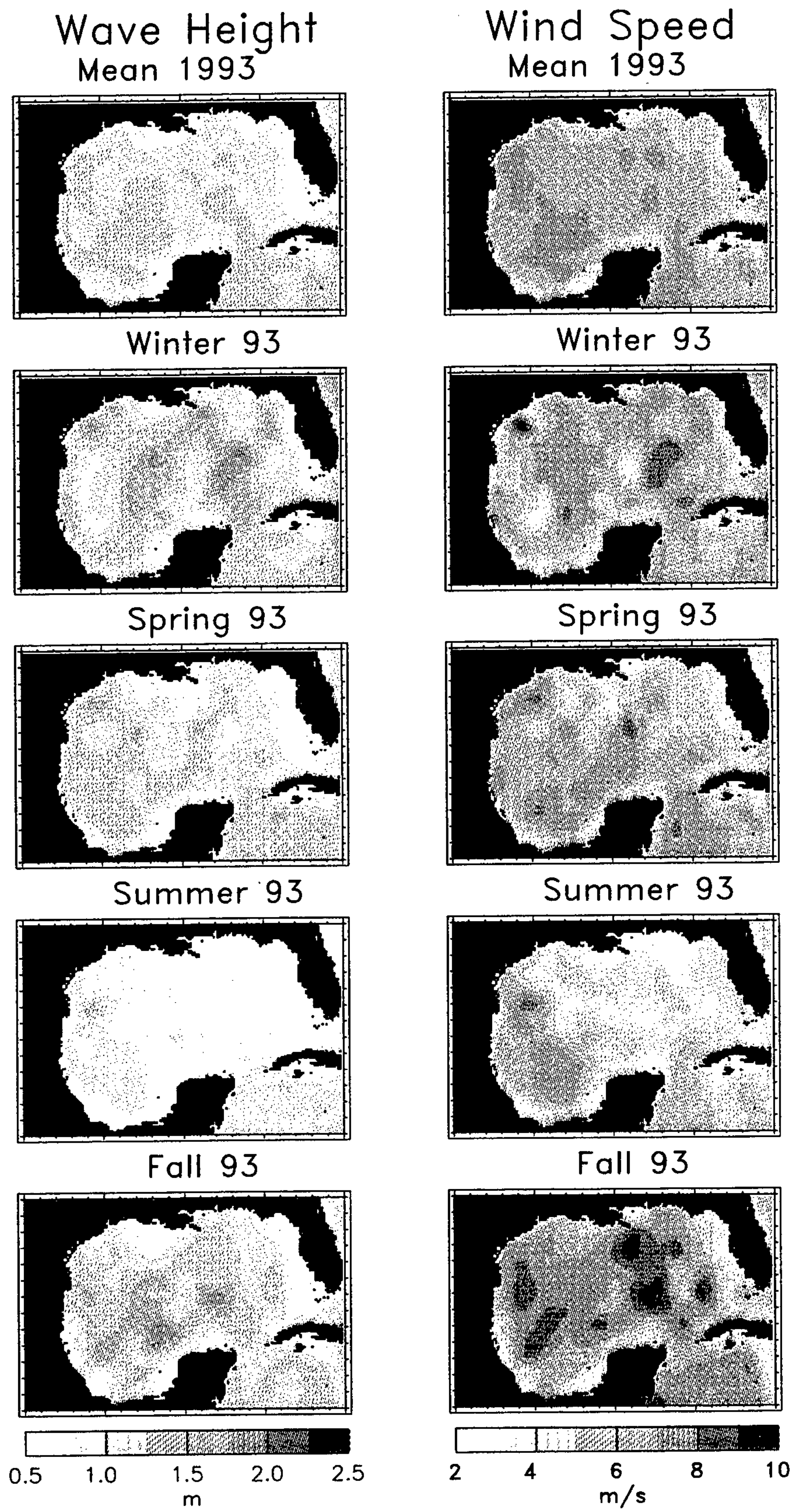

Figure 3. Annual and seasonal mean significant wave heights and wind speeds for 1993.

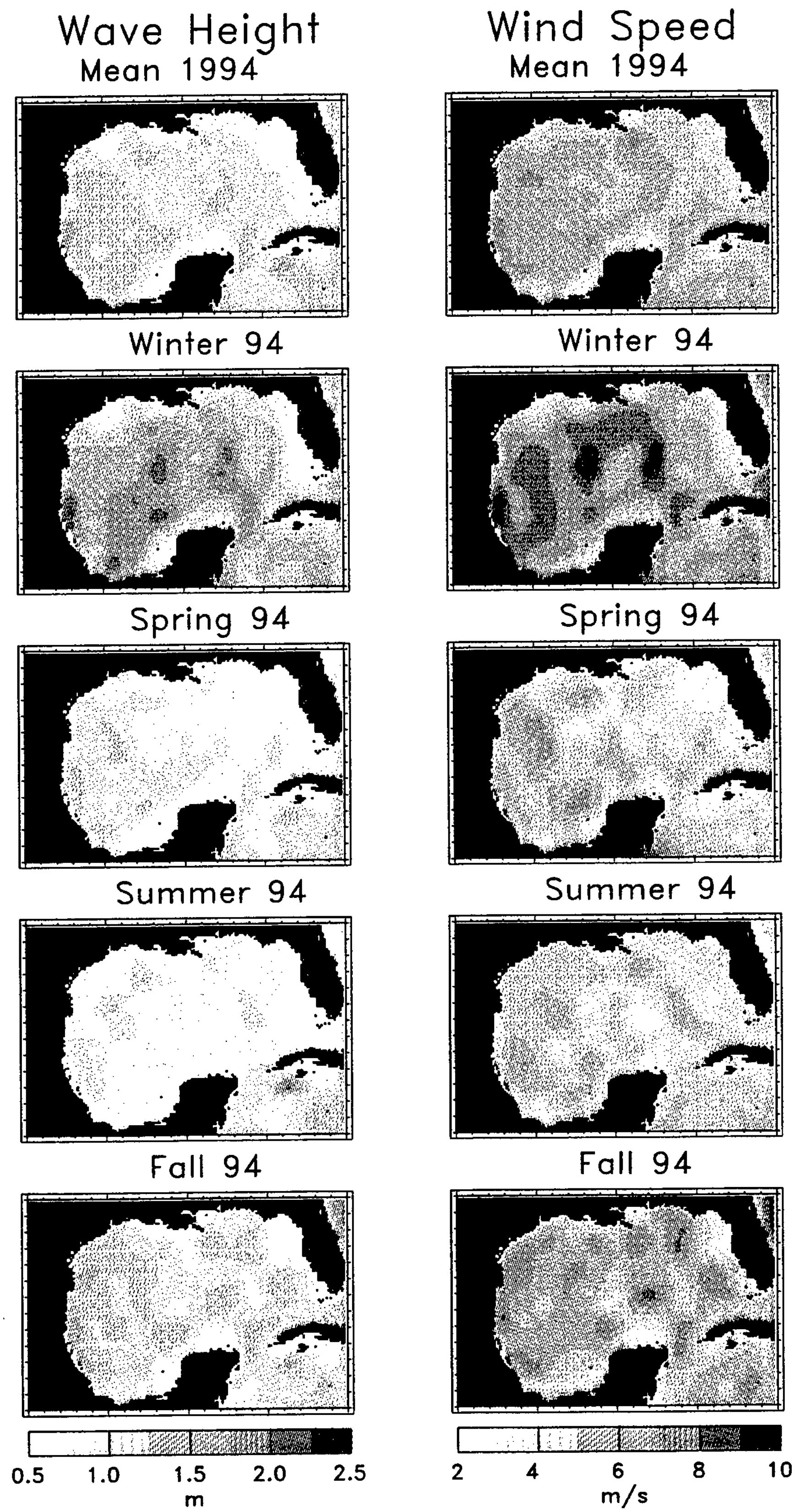

Figure 4. Annual and seasonal mean significant wave heights and wind speeds for 1994.

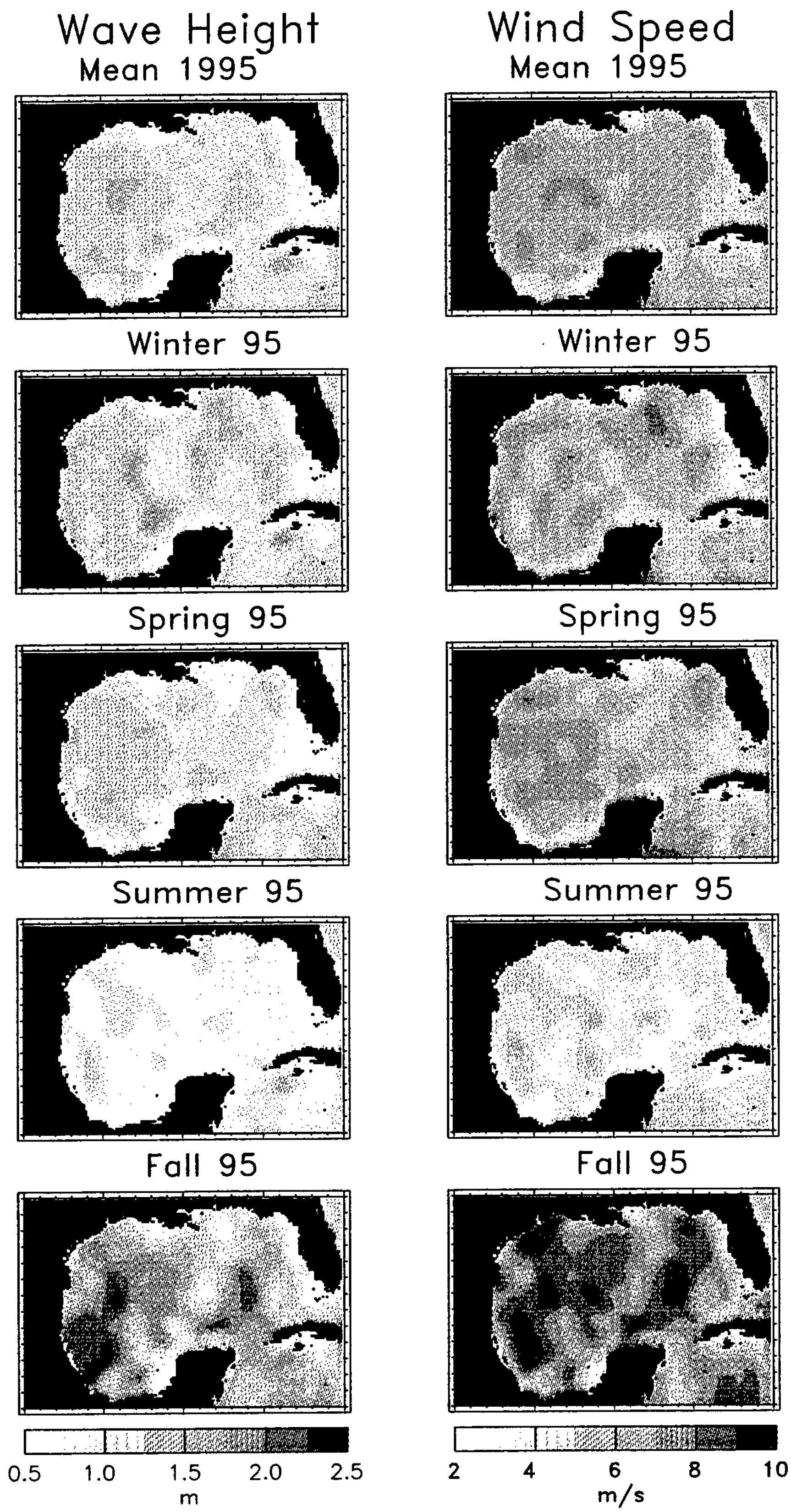

Figure 5. Annual and seasonal mean significant wave heights and wind speeds for 1995.

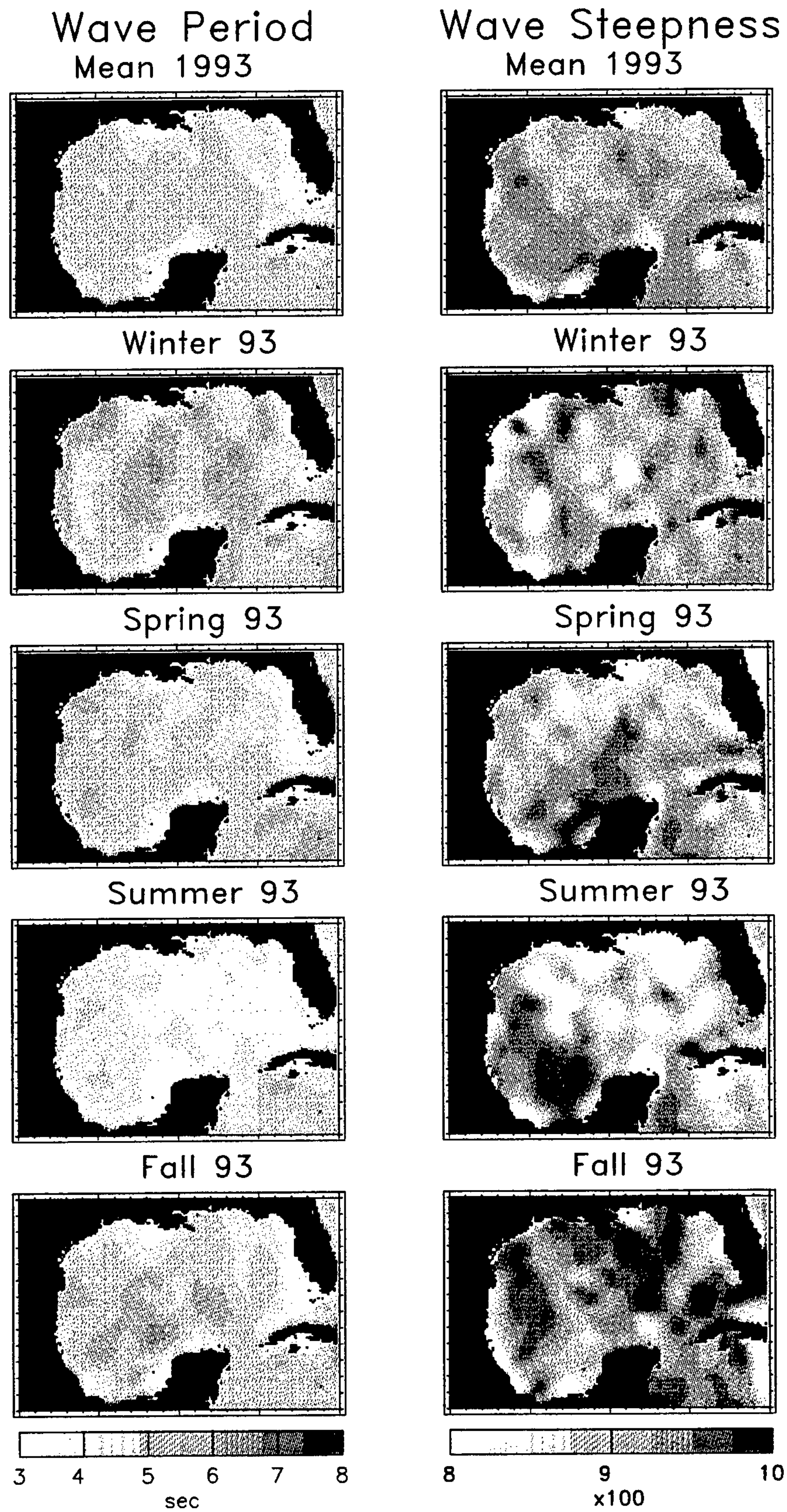

Figure 6. Annual and seasonal mean wave periods and wave steepnesses for 1993.

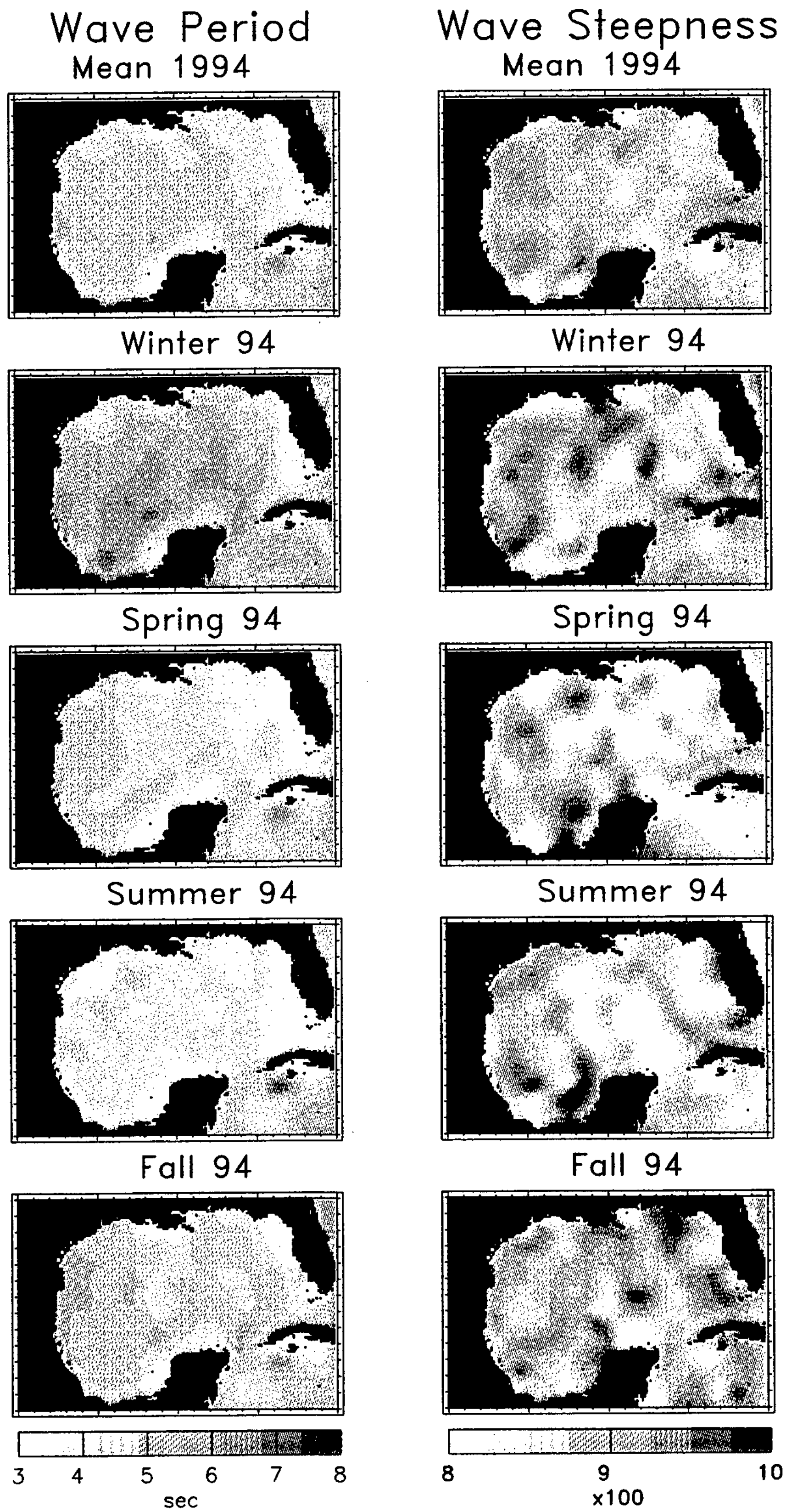

Figure 7. Annual and seasonal mean wave periods and wave steepnesses for 1994.

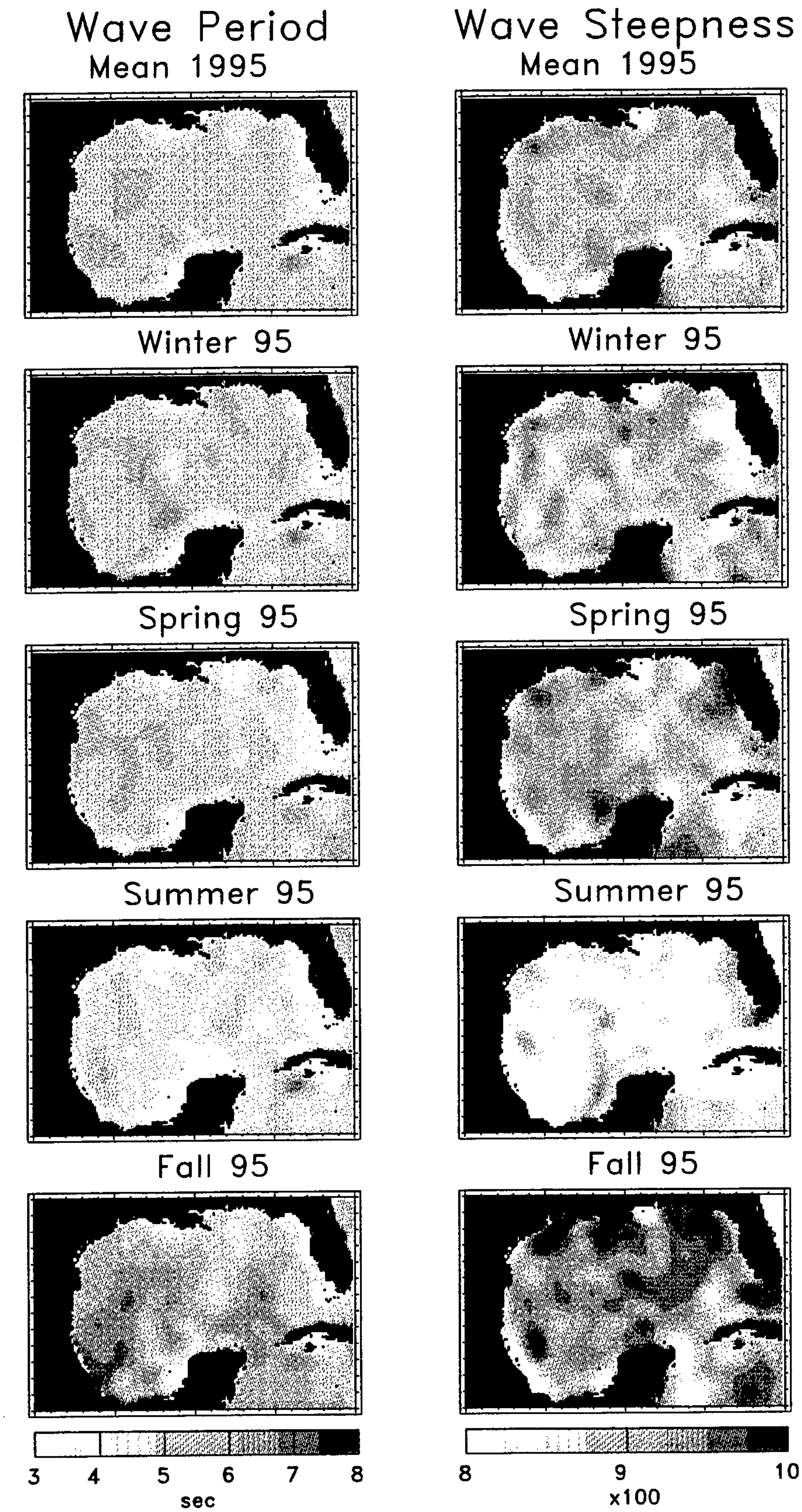

Figure 8. Annual and seasonal mean wave periods and wave steepnesses for 1995.

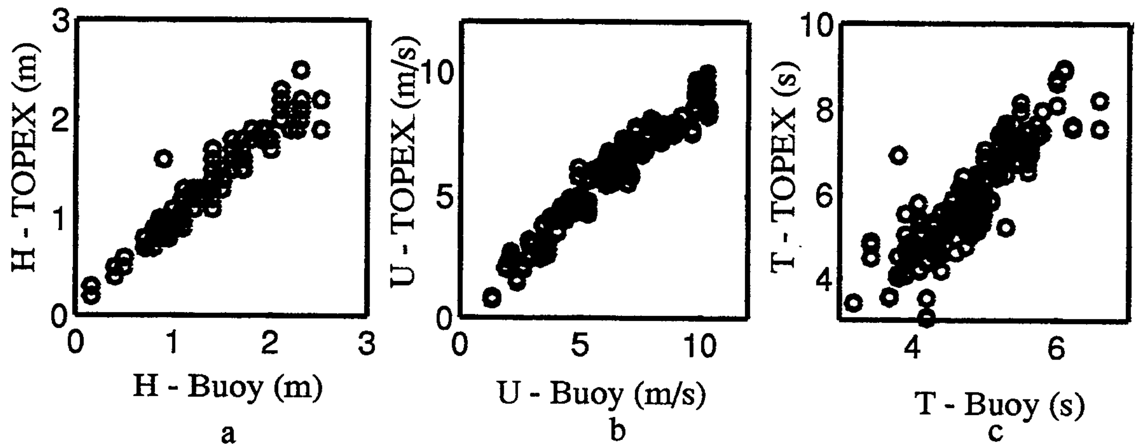

Figure 9. Comparison of TOPEX measurements with NDBC buoy measurements of (a) significant wave height, (b) reference wind speed at 10 m height, and (c) characteristic wave period. The buoy is located near the cross over of TOPEX tracks 20 and 115 in the northwestern Gulf of Mexico, within 30 minutes time of the TOPEX pass.

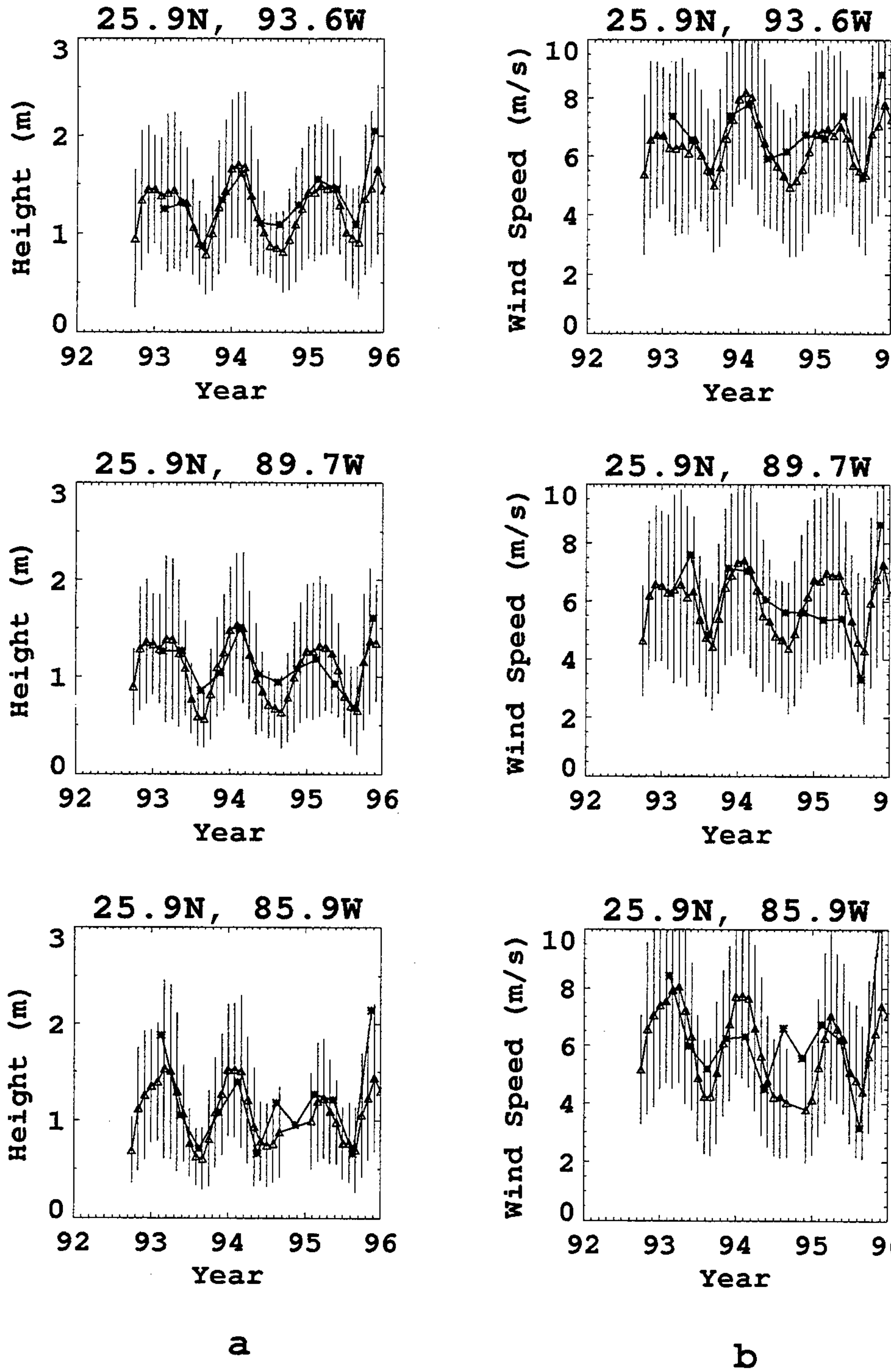

Figure 10. Mean seasonal significant wave heights and wind speeds from the TOPEX-derived climatological maps shown in Figures 2 - 4 (*) compared with monthly mean wave heights (a) and wind speeds (b) from the 3 NDBC buoys located near 26N (Δ). The vertical bars indicate the standard deviation of wave heights and wind speeds calculated from hourly buoy measurements for each month.

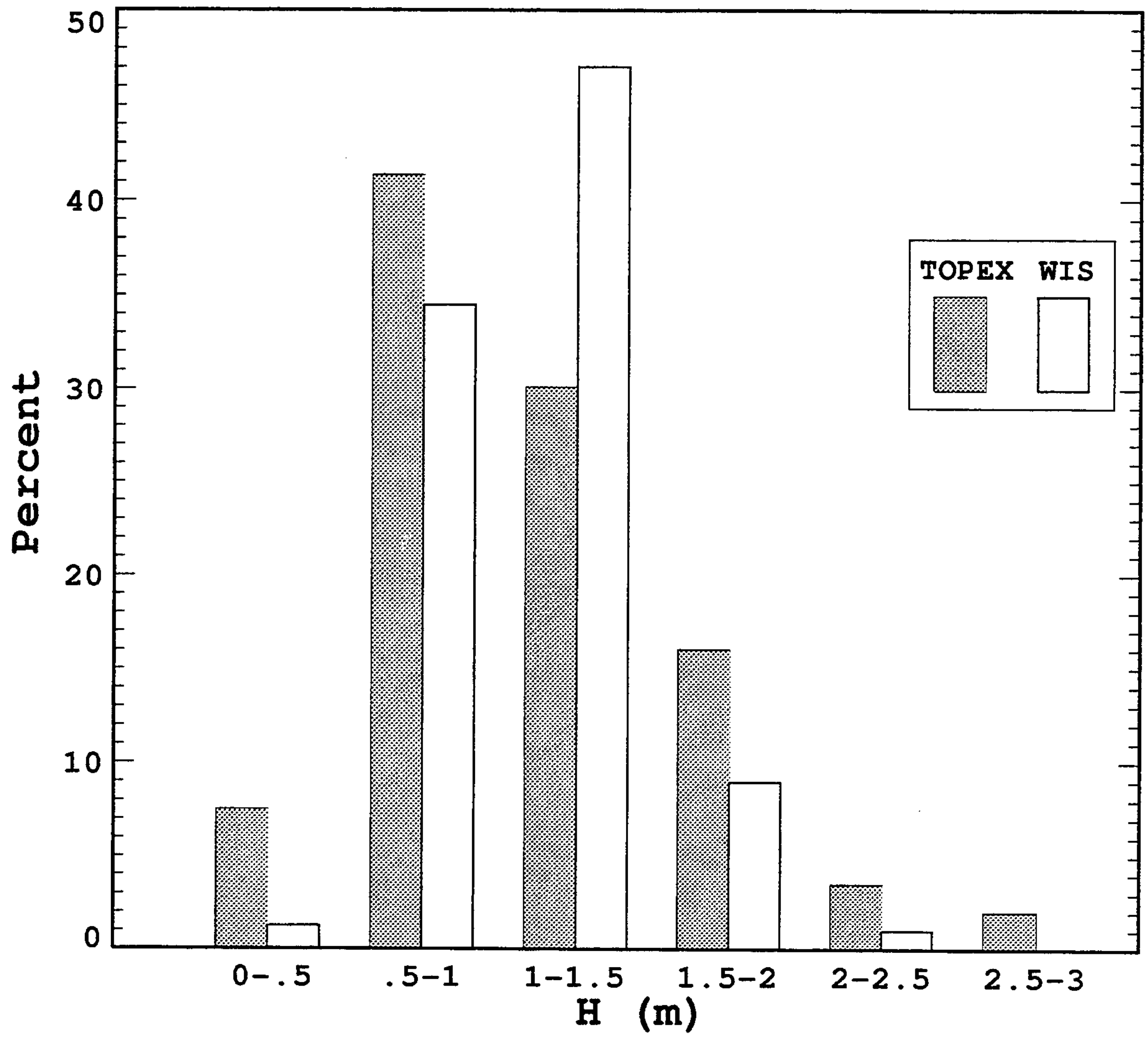

Figure 11. Percent occurrence of wave heights from TOPEX data from ground track 21 are compared with 20 years of data from WIS station 9, located about 5 km from the ground track.